supporting documents

The Detection of Soybean Bacterial Blight Based on Polarization Spectral Imaging Techniques

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In this study, the polarization bidirectional reflectance distribution function (pBRDF) theory was used to establish the experimental measurement platform, in order to obtain the polarization reflectance spectral image of soybean leaves. Soybean leaves belong to a complex surface material. In order to characterize the polarization characteristics of the target and analyze the reverse process between the characteristics of scattered light, the relationship between incident radiation and reflected light is analyzed by using the Mueller matrix reflected by Fresnel and the pBRDF transmitted by micro panel theory, as shown in Figure S.1, the geometric path in the pBRDF model.

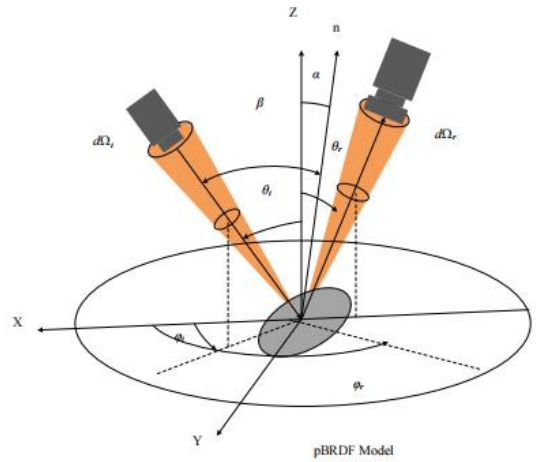

Figure S1. Geometric path diagram of PBRDF model

When interacting with the Mueller matrix (4×4) reflected by Fresnel in the TS-BRDF model, pBRDF can be expressed as:

$$f(\theta_i, \phi_i, \theta_r, \phi_r, \lambda) = \frac{1}{2\pi}\frac{1}{4\sigma^2}\frac{1}{cos^4\,\alpha}\frac{exp(-(tan^2\,\alpha/2\sigma^2))}{cos(\theta_i)\,cos(\theta_r)}M(\theta_i, \theta_r, \phi_i, \phi_r, \lambda) \tag{1}$$

In equation (1), $M(\theta_i, \theta_r, \varphi_i, \varphi_r)$ is the Mueller matrix of Fresnel reflection is represented by the parameter of amplitude, and the dispersion of the amplitude parameter is introduced. By taking the matrix M and combining it into the form of a Stokes vector representation M, we can obtain the M matrix:

$$\begin{pmatrix} \frac{1}{2}(|S_{11}|^2 + |S_{12}|^2 + |S_{22}|^2 + |S_{21}|^2) & \frac{1}{2}(|S_{11}|^2 - |S_{12}|^2 - |S_{22}|^2 + |S_{21}|^2) & Re(S_{11}S_{12}^* + S_{21}S_{22}^*) & -Im(S_{11}S_{12}^* + S_{21}S_{22}^*) \\ \frac{1}{2}(|S_{11}|^2 + |S_{12}|^2 - |S_{22}|^2 - |S_{21}|^2) & \frac{1}{2}(|S_{11}|^2 - |S_{12}|^2 + |S_{22}|^2 - |S_{21}|^2) & Re(S_{11}S_{12}^* - S_{21}S_{22}^*) & -Im(S_{11}S_{12}^* - S_{21}S_{22}^*) \\ Re(S_{11}S_{21}^* + S_{12}S_{22}^*) & Re(S_{11}S_{21}^* - S_{12}S_{22}^*) & Re(S_{11}S_{22}^* + S_{12}S_{21}^*) & -Im(S_{11}S_{22}^* - S_{12}S_{21}^*) \\ Im(S_{11}S_{21}^* + S_{12}S_{22}^*) & Im(S_{11}S_{21}^* - S_{12}S_{22}^*) & Im(S_{11}S_{22}^* + S_{12}S_{21}^*) & Re(S_{11}S_{22}^* - S_{12}S_{21}^*) \end{pmatrix} \tag{2}$$

The directional hemispherical reflectance (DHR) of the soybean leaf surface to be tested is:

$$DHR(\theta_i) = \int f(\theta_i, \theta_r, \phi_i, \phi_r, \lambda)\,cos\,\theta_r\,d\Omega_r \tag{3}$$

From the above equation: $d\Omega_r = sin\,\theta_r\,d\theta_r d\varphi_r$, where θ_i represents the incident angle, θ_r represents the reflection angle, and φ_i represents the incident azimuth Angle, where φ_r represents the reflection azimuth, α represents the angle between the normal direction of the micro element and the normal direction of the blade surface, and σ represents surface roughness of the blade. If the radiation parameters of incident light and reflected light using Stokes vectors are used, then the S^r of the reflected light is S^i from the incident.

$$\begin{pmatrix} S_0^r \\ S_1^r \\ S_2^r \\ S_3^r \end{pmatrix} = \begin{pmatrix} \int f_{00}\,cos\,\theta_r\,d\Omega_r & \int f_{01}\,cos\,\theta_r\,d\Omega_r & \int f_{02}\,cos\,\theta_r\,d\Omega_r & \int f_{03}\,cos\,\theta_r\,d\Omega_r \\ \int f_{10}\,cos\,\theta_r\,d\Omega_r & \int f_{11}\,cos\,\theta_r\,d\Omega_r & \int f_{12}\,cos\,\theta_r\,d\Omega_r & \int f_{13}\,cos\,\theta_r\,d\Omega_r \\ \int f_{20}\,cos\,\theta_r\,d\Omega_r & \int f_{21}\,cos\,\theta_r\,d\Omega_r & \int f_{22}\,cos\,\theta_r\,d\Omega_r & \int f_{23}\,cos\,\theta_r\,d\Omega_r \\ \int f_{30}\,cos\,\theta_r\,d\Omega_r & \int f_{31}\,cos\,\theta_r\,d\Omega_r & \int f_{32}\,cos\,\theta_r\,d\Omega_r & \int f_{33}\,cos\,\theta_r\,d\Omega_r \end{pmatrix} \begin{pmatrix} S_0^i \\ S_1^i \\ S_2^i \\ S_3^i \end{pmatrix} \tag{4}$$

In the system, the vector representation S^{in} that enters polarized reflection transmission can be (atmospheric radiation interference is ignored during transmission):

$$S^{in} = S^r = \int f(\theta_i, \phi_i, \theta_r, \phi_r, \lambda)\,cos\,\theta_r\,d\Omega_r \cdot S^i \tag{5}$$

The indoor lighting source used in this study is a xenon lamp. A polarizer is placed in front of the light source to produce linearly polarized light with a polarization angle of 0°, So S^i can be expressed as:

$S^i = [1\ 1\ 0\ 0]^T$, Due to the correlation between the surface S^{in} of the blade and f_{00}, f_{10}, f_{20}, and f_{30}. f_{00} to f_{30} can be obtained through the Mueller matrix of Fresnel reflection, and from the Mueller matrix, when non polarized $m_{00} \neq m_{11}$, the M matrix at this time can be obtained as:

$$\begin{pmatrix} m_{00} & m_{01} \\ m_{10} & m_{11} \\ m_{20} & m_{21} \\ m_{30} & m_{31} \end{pmatrix} = \begin{pmatrix} \frac{1}{2}(|S_{11}|^2 + |S_{12}|^2 + |S_{22}|^2 + |S_{21}|^2) & \frac{1}{2}(|S_{11}|^2 - |S_{12}|^2 - |S_{22}|^2 + |S_{21}|^2) \\ \frac{1}{2}(|S_{11}|^2 + |S_{12}|^2 - |S_{22}|^2 - |S_{21}|^2) & \frac{1}{2}(|S_{11}|^2 - |S_{12}|^2 + |S_{22}|^2 - |S_{21}|^2) \\ Re(S_{11}S_{21}^* + S_{12}S_{22}^*) & Re(S_{11}S_{21}^* - S_{12}S_{22}^*) \\ Im(S_{11}S_{21}^* + S_{12}S_{22}^*) & Im(S_{11}S_{21}^* - S_{12}S_{22}^*) \end{pmatrix} \tag{6}$$

When describing the incident light field in the second coordinate system, $\vec{E}r = \alpha\vec{E}i$ is represented in the form of a matrix : $\begin{pmatrix} a_{ss} & 0 \\ 0 & a_{pp} \end{pmatrix}$, and introduced as a scalar, the polarization of the BRDF model takes into account the rotation angles η_i and η_r inside the plane. At this point, the resulting matrix is defined as:

$$\begin{pmatrix} E_s^r \\ E_p^r \end{pmatrix} = \begin{pmatrix} \cos(\eta_r) & \sin(\eta_r) \\ -\sin(\eta_r) & \cos(\eta_r) \end{pmatrix} \begin{pmatrix} a_{ss} & 0 \\ 0 & a_{pp} \end{pmatrix} \begin{pmatrix} \cos(\eta_i) & \sin(\eta_i) \\ -\sin(\eta_i) & \cos(\eta_i) \end{pmatrix} \begin{pmatrix} E_s^i \\ E_p^i \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} E_s^i \\ E_p^i \end{pmatrix} \tag{7}$$

In equation (7), the expressions for η_i and η_r are:

$$\begin{aligned} cos(\eta_i) &= \{[cos(\theta_i) + cos(\theta_r)]/[2\,cos(\gamma)] - cos(\theta_i)cos(\gamma)\}/\,sin(\theta_i)\,sin(\gamma) \\ cos(\eta_r) &= \{[cos(\theta_i) + cos(\theta_r)]/[2\,cos(\gamma)] - cos(\theta_r)cos(\gamma)\}/\,sin(\theta_r)\,sin(\gamma) \end{aligned} \tag{8}$$

The M matrix can be expressed as:

$$\begin{pmatrix} m_{00} & m_{01} \\ m_{10} & m_{11} \\ m_{20} & m_{21} \\ m_{30} & m_{31} \end{pmatrix} = \frac{1}{2} \begin{pmatrix} \left(|a_{ss}|^2 + |a_{pp}|^2\right) & cos(2\eta_l)\left(|a_{ss}|^2 - |a_{pp}|^2\right) \\ cos(2\eta_r)\left(|a_{ss}|^2 - |a_{pp}|^2\right) & cos(2\eta_r)\,cos(2\eta_l)\left(|a_{ss}|^2 + |a_{pp}|^2\right) \\ sin(2\eta_r)\left(|a_{ss}|^2 - |a_{pp}|^2\right) & cos(2\eta_r)\,sin(2\eta_l)(a_{ss}a_{pp}^* + c.c.) - sin(2\eta_r)\,sin(2\eta_l)\left(|a_{ss}|^2 - |a_{pp}|^2\right) \\ 0 & 2i\,sin(2\eta_l)\left(a_{ss}a_{pp}^* - a_{ss}^*a_{pp}\right) \end{pmatrix} \tag{9}$$

From the above equation, it can be concluded that the expression of S^{in} with respect to the four Stokes vectors I, Q, U, and V of the incident light is:

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} S_0^{in} \\ S_1^{in} \\ S_2^{in} \\ S_3^{in} \end{pmatrix} = \begin{bmatrix} \frac{1}{8\pi\sigma^2}\int \frac{1}{cos^4\alpha}\frac{exp(-(tan^2\alpha/2\sigma^2))}{cos(\theta_i)}\left[2\,cos^2(\eta_i)|a_{ss}|^2 + 2\,sin^2(\eta_i)|a_{pp}|^2\right]d\Omega \cdot I_{bg} \\ \frac{1}{8\pi\sigma^2}\int \frac{1}{cos^4\alpha}\frac{exp(-(tan^2\alpha/2\sigma^2))}{cos(\theta_i)}cos(2\eta_r)\left[2\,cos^2(\eta_i)|a_{ss}|^2 - 2\,sin^2(\eta_i)|a_{pp}|^2\right]d\Omega \cdot I_{bg} \\ \frac{1}{8\pi\sigma^2}\int \frac{1}{cos^4\alpha}\frac{exp(-(tan^2\alpha/2\sigma^2))}{cos(\theta_i)}\begin{Bmatrix} sin(2\eta_r)\left[2\,sin^2(\eta_i)|a_{ss}|^2 + 2\,cos^2(\eta_i)|a_{pp}|^2\right] \\ +\,cos(2\eta_r)\,sin(2\eta_i)(a_{ss}\,a_{pp}^* + a_{ss}^*a_{pp}) \end{Bmatrix} \\ \frac{1}{8\pi\sigma^2}\int \frac{1}{cos^4\alpha}\frac{exp(-(tan^2\alpha/2\sigma^2))}{cos(\theta_i)}\left[2i\,sin(2\eta_i)(a_{ss}\,a_{pp}^* - a_{ss}^*a_{pp})\right]d\Omega \cdot I_{bg} \end{bmatrix} \tag{10}$$

Real time information on the polarization characteristics of the blades can be obtained from equation (10), where I represents the radiation energy of the incident light in the experimental setup per unit area; Q and U represent the intensity and direction of linearly polarized light; V is the circular polarization parameter in the incident light, I_{bg} is the background light intensity. Through the above equation, it can be found that there are some important factors that affect the polarization state when detecting blades, such as target surface texture, incident and reflected light angles, background light intensity, etc. In addition, wavelength can also affect the polarization characteristics of the target. In summary, when constructing experimental collection devices, it is necessary to fully consider the effects and influences of the various factors mentioned above.

Hardware index and overall parameters of imager

The LCTF spectrum coverage of the liquid crystal tunable filter is 400nm~720nm, with fast response speed and good sensitivity. The specific parameters are shown in Table S1.

Table S1 LCTF effective parameter index

Parameter	Index
Wavelength accuracy	FWHM/8 ± 0.5nm
FWHM	7 、10 or20nm
Optical response time	50ms
Operating band	400~720nm
Optimum operating temperature	10~40℃
Transmission and power supply mode	USB
Effective aperture	22 or 35

The specific parameters of CCD detector are shown in Table S2

Table S2 CCD effective parameter index

Parameter	Index
Resolving power	2048 × 2048
Frame rate	100fps
Response time	1/10000~10s
Sensor type	Area array CCD (monochrome)
Minimum pixel size	6.5 μm × 6.5 μm
Data bits	16 bit
External power supply	36 V
Output noise	﹥40 dB

LCPR parameters of liquid crystal polarization regulator are shown in Table S3. As the polarization angle resolution of this model LCPR is 1 °, it has higher resolution than other models, so this model is selected.

Table S3 LCPR effective parameter index

Parameter	Index
Polarization angle resolution	1°
Measurement range (polarization)	1%~100%
Caliber	76.2 mm
Ellipticity	1: 150